/ ' /') ... ' , .
/'/ ... ' / ... /... /... / ...

Mars Pathfinder Flight System Integration and Test[1]

Brian K. Muirhead
Mars Pathfinder Flight System Manager
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
818-393-1013
brian.k.muirhead@jpl.nasa.gov

Abstract-This paper describes the system integration and test experiences, problems and lessons learned during the assembly, test and launch operations (ATLO) phase of the Mars Pathfinder flight system scheduled to land on the surface of Mars on Jul y 4, 199-/. Mars Pathfinder is one of the new series of small, challenging missions doing significant science/engi neering cm a fast schedule and cost capped budget. Pathfinder follows in the footsteps and goes beyond the very successful Viking mission of 1976.

The Mars Pathfinder spacecraft is actually three spacecraft: cruise stage, ent ry vehicle and lander. The cruise stage carries the entry and lander vehicles to Mars and is jettisoned prior to entry. The retry vehicle, including aeroshell, parachute and deceleration rocket s, protects the lander during the direct entry and reduces its velocity from 7.6 to () km/s in stages during the 5 minute entry sequence. The lander's touchdown is softened by airbags which are retracted once stopped 011 the surface. The lander then uprights itself, opens up fully and begins surface operations including deploying its camera and rover. At the time of this writing the spacecraft is one month from launch (Dec. 2, 1 996) following an 1 8 month development and 1 8 month integration and test Cycle.

This paper overviews the system design and the results of the system integration and test activities, including the entry, descent and landing subsystem elements. System test experiences including science instruments, the microrover, Sojourner, and software are discussed. The final qualification of three entry, descent and landing (EDL) subsystems during this period is also discussed. Valuable lessons learned during this phase of development are discussed from the point of view of the new ways of" doing business needed to accomplish this challenging mission within the schedule and cost constraints while still minimizing mission risk. Summary cost data showing the evolution of the budget plans is also presented.

At the time of the final edit of this paper the Mars Pathfinder spacecraft has been successfully launched and is on its way to Mars with all subsystems operating normally. We are well within our cost cap of $171 M.

[1] The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

TABLE OF CONTENTS

1. INTRODUCTION

The mission objectives of Mars Pathfinder are:

- Demonstrate a simple, reliable and low cost system for placing science payloads on the surface of Mars.

- Demonstrate NASA's commitment to low cost planetary exploration.

- Assess the structure of the Martian atmosphere, determine elemental composition of rocks and soil, investigate surface geology and mineralogy of rocks and acquire meteorology data at the surface.

- Demonstrate the mobility and usefulness of a microrover on the surface of Mars.

This paper is written at a point in the project where all flight hardware have been delivered, integration has been completed, system functional and environmental tests have been completed and the spacecraft stands ready for launch at Cape Canaveral. Budget and schedule reserves appear to have been adequate to keep the project within its original schedule and budget constraints. This is no small feat, as some of our most senior review board members commented on the fact that they never thought we'd make it. This paper describes the spacecraft assembly, test and launch operations (ATLO) approach that has come together to produce one of the most exciting and demanding space missions of the last 20 years.

Pathfinder follows in the footsteps of the Successful Viking mission of 1976. Pathfinder drew heavily on the experience of the Viking mission including test data, flight data and some design concepts (parachute and aeroshell). However, with the exception of the full scale, high altitude drop test program, Pathfinder performed the same general level of subsystem and system verification as Viking did, at a much lower cost.

The flight system discussed here is defined as the spacecraft with the science instruments and rover. Once delivered for integration (December, 1995), the science instruments and the rover became part of the flight system.

2. MISSION DESCRIPTION

A single Mars Pathfinder flight system, shown in launch configuration in Figure 1, will be launched to Mars in the period December 2, 1996 to December 31, 1996. The Delta II launch vehicle puts the spacecraft on a Type I trajectory for a landing on the surface of Mars at Ares Valles (19.5 N and 32.8 W) on July 4, 1997. This landing site is about 1000 km from the Viking I site. The flight system is made up of 3 major elements (shown in Figure 2 in exploded view) having distinctly different functions: 1) cruise stage, 2) entry vehicle, and 3) lander. The flight system is spin stabilized during cruise, spinning at 2 rpm, with the spin axis and medium gain antenna pointed primarily to Earth. An Earth point attitude (within about 40 degrees of the

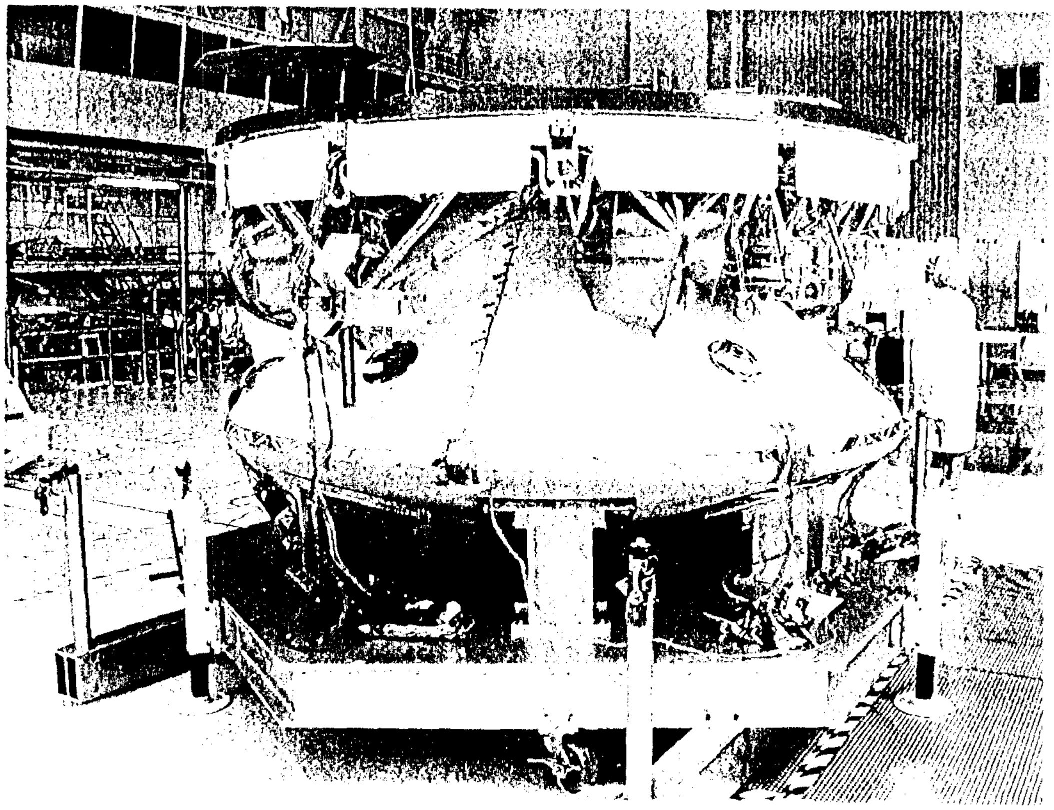

Figure 1. Flight System Assembly, Ready for Launch

Sun) is maintained until Mars atmosphere entry, except during the first 2 of 4 trajectory con ection maneuvers. Downlink communication (mainly to 34m DSN stations) is through a fixed medium gain antenna at 40 bps. During normal cruise the spacecraft is quiet, with attitude control disabled between tile three times per week communications periods. Thirty minutes befoi c Mars atmosphere contact, the flight system will jettison its cruise stage and enter directly into the Mars atmosphere, braking with an aeroshell (the combination of the backshell and heatshield), parachute, small solid retrorockets and air bags in what is called the entry, descent and landing (EDL) phase. The entry velocity is '7.6 km/sec (17,100 mph) compared with Viking>s 4,6 km/sec entry fi om orbit. Mars Pathfinder's entry angle is 14.2 deg. (90 deg. would be straight down) and the peak atmospheric deceleration load of about 20 g's is encountered at 30 km above the surface. The atmospheric structure instrument (ASI) takes measurements during this phase to determine atmospheric density distribution using atmospheric deceleration, pi essure and temperat ure. The pai achute is deployed at about Mach 2.? (1 500 mph) at 9 km altitude, 1 ()() seconds befoi e landing. During the EDL phase, only the carrier will be transmitted to Earth. Various events will be discerned from the doppler signature. A bi nary frequency modulation technique is used to signal specific events such as heat shield separation and acquisition] of altimeter

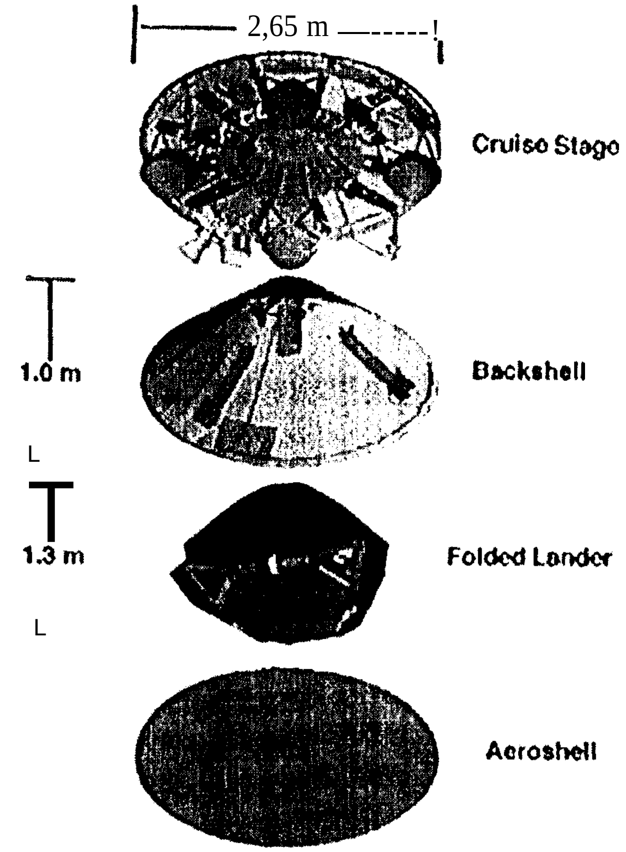

Figure 2. Flight System Assembly, Exploded View

signal. Solid rockets stai It firing at <90 m from the surface and slow the dc.scent from 65 m/s to 0. The bridle is cut at < 30 m from the surface. and Pathfinder then free falls to a landing at less than 15 m/s (33 mph) vertical and up to 2 (J m/s (44 mph) horizontal velocity. Landing loads arc limited to <45 g's using an air bag system designed with sufficient stroke to accommodate 1/2 m size rocks without contacting the lander. The lander bounces and rolls to a stop. After I] ( ) more motion is detected, the airbags are deflated by opening a vent and arc retracted back to the petal surfaces. The lander thin) rights itself using 3 actuators whit]) open the petals of the tetrahedral lander like a flower.

The petals have solar panels on their inside. surfaces which power the spacecraft for surface operations. The lander fully assembled, in the. final stages of assembly at KSC, is shown in Figure 3. Figure 4 shows the deployed lander. After uprighting and opening, the lander will first transmit stored EDL data and rca] time lander and rover engineering telemetry, completing a major mission objective. Under nominal conditions, the stereo imager for Mars Pathfinder (IMP) will then be deployed to locate the sun to determine of' the lander orientation and thereby to enable high gain antenna communication dire.dly to Earth. IMP will then usc its 12 spectral channel, CCD camera

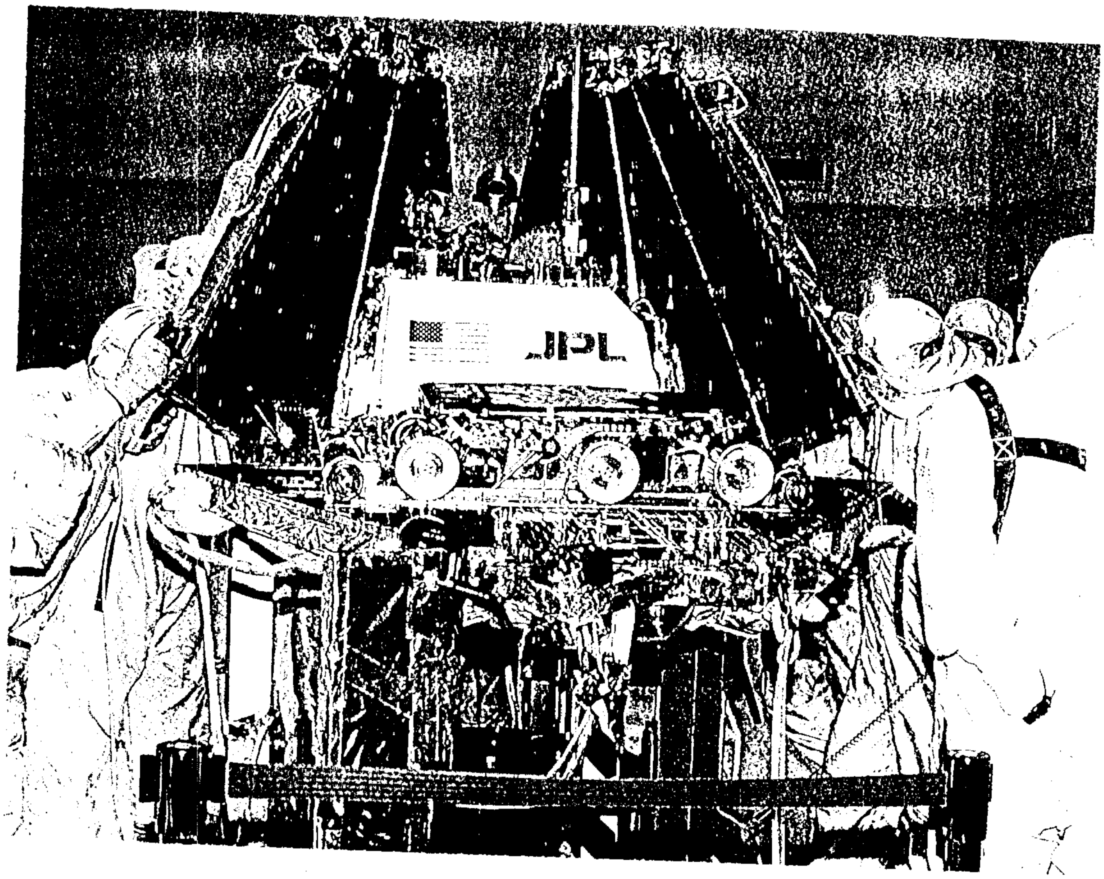

Figure 3. Lander, Fully Assembled

to generate a panorama of the surface, image the atmosphere and support rover navigation.

It is planned to deploy the rover for the start of its surface operations mission on the first day. The rover conducts surface mobility experiments, images rocks and soil and deploys the alpha-X-ray-proton spectrometer (APXS) for making elemental composition measurements of soil and rocks. The mobile rover enables direct measurements of Mars rocks to determine mineralogy which was not possible on the Viking mission. The rover carries forward and aft looking cameras for demonstrating autonomous hazard avoidance and imaging its local surroundings, soil and rocks, and the lander.

The lander primary mission is thirty sols (1 sol = 24.6 hrs). Nearly 100% of all lander and rover engineering and science objectives will be achieved in the first few days of surface operations. Currently, no constraints preclude operations of the lander beyond the primary mission although lifetime is most likely limited by the battery cycle life and large thermal Cycle (-40 to +40 each sol) stress on some electronic assemblies.

3. System Testing

The assembly, test and launch operations (ATLO) phase was planned and started in mid-June, 1995 for an 18 month period. This

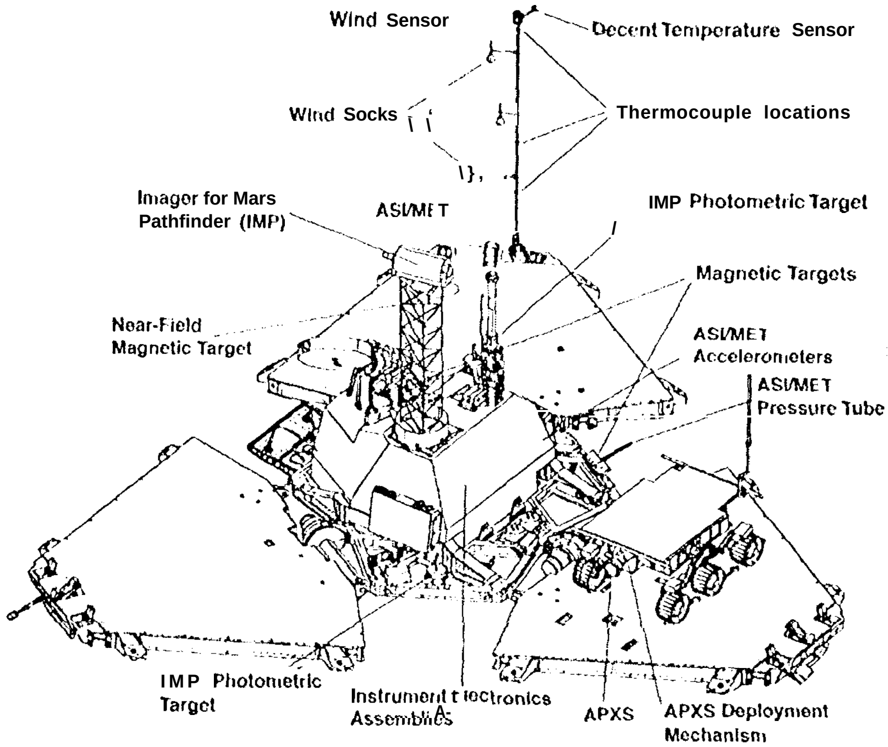

Figure 4, Deployed Lander Configuration

was an unusually long ATLO phase for a 3 development but it was necessary to get the, time on the electronics and to assemble such a complex mechanical systc.in. This phase stalled with the initial deliveries of the power and attitude and information management (AIM) electronics and cabling. We then integrated the telecommunications subsystem and conducted subsystem-level vibration and centrifuge tests to dynamically verify the core. electronics for launch and landing. We then entered into a sequential build up of hardware and software leading up to final lander assembly in February, 1996. Along with this build up we conducted 6 major system tests with progressively more complete hardware and software in the loop. These tests were conducted in the various spacecraft operating modes (e.g. pre-launch, launch, cruise, EDL, surface) and were intended to be complete end-to-end tests. For example, the first two system tests used fright S/W delivered with device drivers, uplink, downlink and attitude control. Some science, some EDL and some fault protection capabilities were also included which allowed us to perform primarily launch and cruise phase testing as well as initial EDL, surface and rover testing. The results of these tests Were extremely valuable in directing specific changes in flight S/W, particularly EDL.

Once the lander was completely assembled (Feb. 96) we entered the environmental and functional test phase. The hardware was built up sequentially from lander to entry vehicle to cruise/launch configuration (see Figure 2). In the launch configuration we conducted the system acoustic, EMI tests, the spin balance measurement and the cruise solar thermal vacuum tests. The acoustic test was without incident but the solar thermal test showed 2 significant problems: the solar array was running 30C hotter than predicted, resulting in lower voltages throughout the mission and therefore less power, and the propellant lines to the thrusters were running 20C too cold. These 2 problems are related to a lack of detailed modeling of the significant blockage of the bad of the solar array due to propulsion and electronic hardware. The propellant line thermostats were not adequately isolated from the hot solar array which caused the thermostats to be off while lines seeing deep space got cold. The propellant line problem was fixed by improving the blanket design and adding parabolic reflectors that further isolated the propellant lines from the solar array. We had enough margin to swallow the power loss.

At the start of this phase we were about 8 months from launch and the software suite now included 90% of its required functionality. We thought we were in software heaven; we said nobody had ever had this much flight S/W in place this early. Systems tests 3 and 4 now included full up launch and cruise testing including plugs-out tests and DSN compatibility. EDL was run with monitors on all pyro events to verify correct timing and multiple surface sequences were run including fault protection and contingency sequences.

Following the cruise thermal vacuum testing we now simulated the mission sequence by firing pyro release devices and disassembling the spacecraft. We ended this process with the lander opened, on the floor of JPL's 25 ft space simulator chamber to simulate the Mars surface conditions. We used an 8 torr GN2 atmosphere (the first time a cold wall test with an internal atmosphere had ever been run) and conducted tests including diurnal cycles and steady state conditions. These tests included the rover waking up on Sol 1 and driving off the lander petal. This test verified the surface model predictions very well.

It was now July, 1996. We had completed all our environmental tests, we had 99% of our functionality in S/W and we again conducted a full up, all H/W in the loop, end-to-end mission test. As in all the previous tests, we found problems we needed to fix. By this time the S/W and engineering model testbeds were running about 24 hours per day with fixes, retests and robustness testing.

We shipped the lander and aeroshell/cruise assemblies by truck to Kennedy Space Center, leaving at midnight on August 10th (2 weeks ahead of our original ship date) and arrived 60 hours later. Leaving early gave us more margin for assembly and allowed us to insert another end-to-end system test at KSC.

At KSC we now started the full up assembly process as we had back in February. This process started with the lander torn down to its electronic chassis for verification of power relays and replacing 2 fuses that had been blown (See "Software can hurt hardware" below). We installed the flight battery on the lander and radioisotope heater units into the rover and started close out operations working 8-12 hours per day, 6 days a week. We completed entry vehicle assembly on Oct 14, 2 months after arrival.

4. FINAL EDL SUBSYSTEM QUALIFICATION

While the spacecraft was undergoing its testing at JPL, three EDL subsystems were completing their qualification testing. The parachute, RAD rockets, airbag, and radar altimeter could not be functionally tested in the ATLO environment, so this work was done in parallel with ATLO and the qualified hardware delivered to KSC.

The parachute qualification program went off without any problems. In fact, the vendor, Pioneer Aerospace, was so confident in their design that they subjected one of the qualification units to a dynamic overpressure test of greater than 3 times flight limit load and the parachute survived undamaged.

The rocket assisted deceleration (RAD) subsystem uses 3, >15600 N-sec impulse rockets, based on Titan solid rocket booster separation motors and using space qualified propellant. The RAD rockets experienced a unique problem during a live fire drop test at China Lake Naval Air Warfare Center. While using a simulated backshell, a set of flight configuration rockets experienced an instability while burning; this resulted in higher chamber pressures and an earlier burnout of the motor. After much analysis and discussion with experts it was decided that the only reasonable fix was to increase the fraction of aluminum in the propellant back up to 16% from 2%. We had reduced the Al level to reduce contamination of the surface for science measurements. We ordered the flight set of motors built with the 16% Al and proceeded to test our last set (3) of 2% motors in the same simulated backshell we had used before. We te.tile.l'c(i the assembly rather than dropping it so we could fully instrument it. Fortunately or unfortunately, we could not reproduce the instability. We took one final step to convince ourselves we were OK. We took the flight spare backshell (graphite composite with thermal protection materials applied), loaded three 16% Al rockets into it and fired them. The burn was nominal, no sign of instability. We were fairly confident the core problem had been an interaction between the motor dynamics and the test structure. The flight structure was much better damped with very little transmission of energy from one motor to the other. The qualification set of 6 motors also performed exactly as expected.

The airbag subsystem (designed by JPL and built by ILC Dover) is a completely new design which uses gas pressurized Vectran bags. The gas generators (built by Thiokol) pressurize the bags to 6800 pascals (1.0 psi). The 4 airbags envelop the lander and cushion its landing at a velocity of about 25 m/s on the rocky Martian terrain. This design completed qualification at Lewis Research Center's Plum Brook Station. The test program started with a fully packed bag assembly which had experienced planetary protection bakeout as well as full environmental qualification. The bag was placed in a cold chamber and inflated using the gas generators (these huge bags inflate in about 0.5 sec.)

This assembly was then taken to the world's largest vacuum chamber (pumped down to 8 torr, Mars ambient) with 120 ft of vertical height and 100 ft working floor space. Here the full scale assembly (4 segments forming a spheroid with overall diameter of about 5 m), was dropped onto a rock field representative of the expected landing site. A vertical speed of 28 m/s was selected as bounding 100% of the extensive Monte Carlo simulations run of the landing preconditions. In order to simulate the horizontal velocity in a vertical drop test, the rocky surface was rotated 60% off" tile rim)]'. A final set of retraction and lander deployment tests were also conducted under realistic rock strewn terrain and cold (-100 C) coalitions.

5. LESSONS LEARNED

Mars Pathfinder is one of the first of NASA's missions implemented under the "faster, better cheaper" (FBC) paradigm. The technical and programmatic challenges of this mission development are significant. The development period has been 3 years. The cost cap is $171M (real year $, not including launch vehicle, mission operations or the rover), of which the spacecraft, not including the rover and instruments has spent $135M. The logical comparison is to Viking, which was a 6 year development which today would cost >$3B (Viking was the most expensive planetary space mission ever accomplished). The fundamental difference between Pathfinder and Viking is the approach to risk. Pathfinder must take risks that arc. not typical for planetary spacecraft, including a mainly single string architecture, non-class S electronic parts ant] limited documentation. Of course, the. mission must also be Successful. Ways of doing business, many (trot made perfect sense 30 years ago, were used that significantly reduced development time and controlled costs while still assuring a highly reliable vehicle. These "new ways of doing business" arc highlighted below in the form of lessons learned.

The excitement about the. mission and the l'reject's commitment to "reinventing" ways of doing business attracted many of JPL's best and brightest. In spite of the long hours and hard work, 1 heard from many people that this is the best project they had ever worked on. *The success of the Mars Pathfinder development proves the old adage that the right team of motivated people, when given a clear target and the resources, can do almost anything.* This project provided an opportunity 10 significantly expand the experience base of a number of engineers. Many developed totally new skills in an environment where no experience existed at JPL (e.g. EDL, entry dynamic simulation, surface operations) and thereby increasing their value to future projects.

Hands-on management is essential for FBC projects. During the integration and test (I & '1') phase the Project operated without individual work package.s but instead relied on detailed test schedules, workforce plans and lien lists to track progress and budget. Hands-on leadership allowed this approach to work. In depth understanding of the technical design, knowledge of programmatic resources, and knowledge of margins (mostly mass) allowed for rapid decision making, saving time and money. Extensive trade studies were not needed to make baseline changes. Real time meetings and memos were used to make and document many decisions. In the latter phases of integration and test, we established a change control process to monitor and limit the scope and number of changes to assure better ideas didn't prevent us from finishing the necessary tasks. This board was made up of the Flight System, Science, MOS, GDS and Rover managers.

A flat organization structure and the co-location of management, systems, ii M, ground data system and mission operations has led to excellent communication and rapid problem resolution. The project-level flight system management was on a first name basis with nearly every member of the team, including cognizant engineers, designers and technicians. Key decisions were able to be made quickly because the management team had a detailed understanding of status, problems, problem ramifications and could work with the cognizant engineers to resolve problems, either technical or programmatic.

An atmosphere of openness, honesty and personal responsibility by every member of the Team is essential. The level of integrit y and commit ment of everyone on the team helped us find and work through problems in record time. Sometimes it seemed like luck that a problem presented itself but more often than not it came from people going just a little bit further, looking beyond their own job responsibility, to find a subtle problem that could have been serious if not resolved. The high reliance on individual team member's knowledge, and communication skills did have a breakdown. The problem of the solar array running 30C too hot and resulting in lower voltages throughout the mission was primarily the result of a communication breakdown between two specialists. The solar array cognizant engineer wanted the most probable temperature and the thermal analyst gave him the worst case cold. In spite of asking this question multiple times the answer still came back wrong. *Everyone, whether hardware engineer, analyst or manager, must wear the bigger system hat and look beyond his own interface/specialty to be sure he understands the other guys problems/ quest ions.*

To a large extent documentation was need driven and informal. Further, we placed a high reliance on individual team member's knowledge, communication skills and commitment to make sure things did not fall through cracks. For integration and test the need fOJ good procedures was debated. 'l'tic! complexity of the mechanical assembly, the need to fully disassemble and reassemble at KSC dictated very good procedures for mechanical assembly and test. On the electronics test side, the possibility of using a streamlined procedure was considered but not implemented due to the tools and approach already in pla ce. The engineering change control process g.c n crated only 34 Engineering Change Requests ant{ 101 software change requests. During the entire ATLO phase the number of change requests and problem reports was remarkably low. Problem reports came from the flight system (spacecraft, science, rover), testbed and mission operations testi ng. The total number of problem reports from ATLO were 229, 63 from Rover, and 514 from the testbed for a total of 806 problem reports. Our big sister Cassini has over 3,000 PR's and has one more year of ATLO to go.

Having a state-of-th e-art processor and writing in 'C' was essential to completing the software job. In spite of our early successes with software development it was still a race to the finish to complete all our development, testing ant] retesting. Wc used the testbed e nvironment extensively to verify all software updates before loading them on the spacecraft. Wc also used the testbed for a wide range of off-nominal and robustness tests. Software team Wrote over 155,000 line.s of code not including the VxWorks operating system. The original estimate was about 20,000. The effective rate for the software. team was about 28 1 ines of bug free flight code per person per day (this is probably a record). The S/W developers ended up addi ng a lot of features that gave us more flexibility but made it harder to test and verify. We would have liked to have more than the 6 Mbyte of EEPROM to store our two full images Of flight software. Overhead demands of the operating system on the RSC-6000 processor p robably resulted in an effective 12 MIP machi ne out of 20 MIP-class p rocessor. *Never underestimate the size of a software task.* We could have used 1-2 JJ10)C people. We lost 3 key programmers toward the end Of the development to new opportunities in the Bay Area but 2. of them commuted back to JPL 10 help us finish the job and fix some complex problems.

Although we expected that our lai gel y single string S/C required much less fault protection design and development than other spacecraft, it made up for it in the relatively complex testing, and validation o f the software. Pathfinder has only two major fault protection algorithms: command 10ss and battery discharge control.

The use of a well known, commercially-based, electron ics in terface (VME) and real - t ime opera ting system (VxWorks, by Wind River Systems) worked well. Once the final vei sion was delivered in April,] 995 we had only one major issue, which was a task scheduling error that was difficult to find and which Wind River Systems worked closely with us to isolate and fix.

Software can hurt hardware so make sure it doesn't!! We discovered, after comm it t i ng to the system design, that our waveguide transfer switch (W-l'S) could not be left powered for more than about 2 minutes without burning out the rotor windings. We designed our software. to protect against such an incident. 1 lowever, a semi-pathological condition occurred during surface f a u l t protection testing in which the software commanded a reset of the WTS but was interrupted before commanding it off. This would not have been a problem if the fault protection had not been using a wrong parameter which caused the S/C to go to sleep for many minutes. As is typical in these cases, it took two errors to create a sei ious problem, but wher c such states can occur they almost always do occur. Following this incident we built a hardware circuit to protect the WTS and, since we couldn't convince ourselves that the software couldn't bite us again, installed it.

The extensive use o f enginee ring model hardware for design performance and environmental qualification worked extremely well. We did not have a single board or part-level failure of any flight hardware during the ATLO phase. This saved us untold time and money and may have been the single most important factor in staying within the cost and schedule constraints.

171C! *use of separate n/w and S/W testbeds for development, tr ouble shooting and mission operat ions sequence validation is essent ial to maintaining cost and schedule.* These two collocated testbeds allowed us to maintain simultaneous S / W development and test environments.

Starting our assembly, test and launch operations (ATLO) phase early (an aggressive 18 months after project start, 18 months before launch) paid off well. We achieved over 2700 h ours of system test time (planned for 1000 hrs with a goal of 2000 hrs).

Once we completed our analysis of the computer dynamic memory (DRAM) radiation sensit ivity, w c. were faced with a large number of potential single event upsets that could cause double bit errors and hence a]c.set of the computer. By design we are using the rc.set (wai m reboot) as the mechanism to correct all software and many hardware related problems. 1 lowever, a worst case frequency of 1 SEU per day is higher than our worst expectations. We made one significant S/W modification because of this concern. Normally, if a page of memory has a double bit error we declare a reset, throw the bad page away and dump all the memory pointers. We modified this approach to allow us to rebuild the memory pointers around the bad

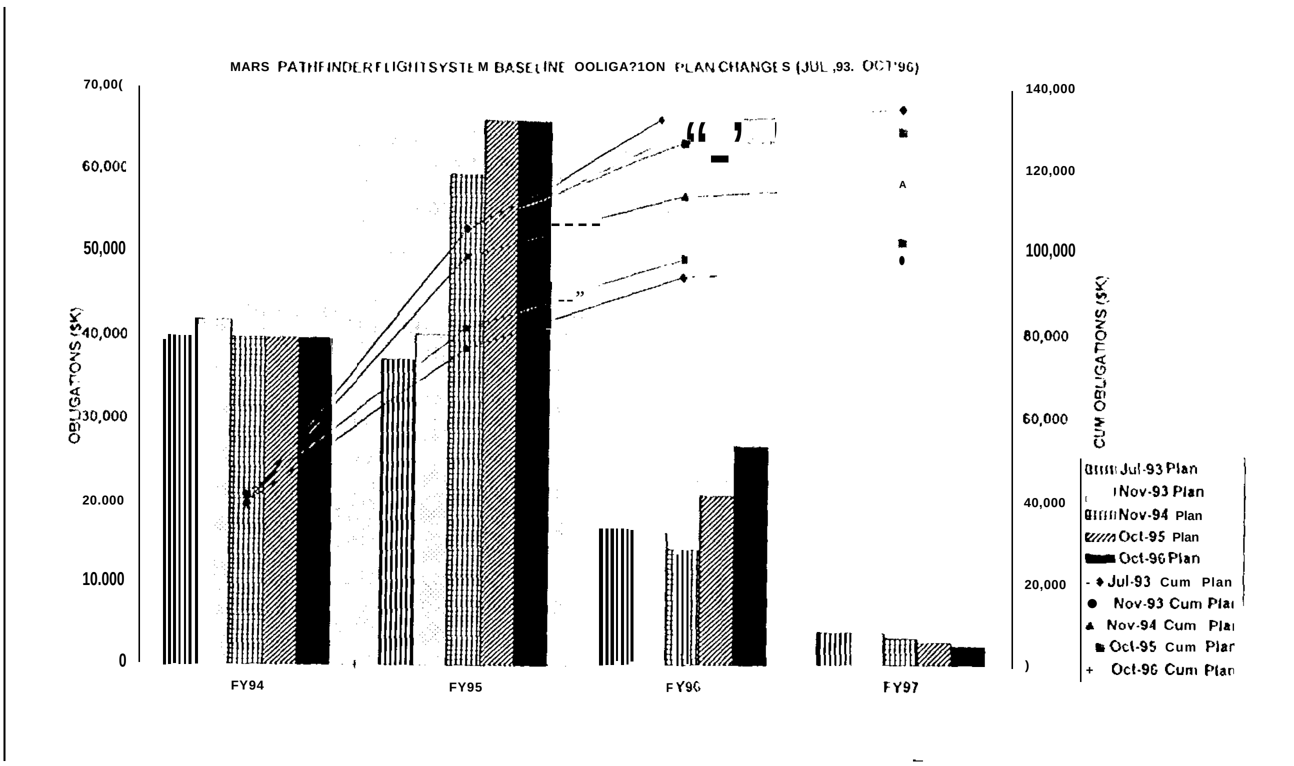

Figure 5. Obligation Plans by Plan Date

page and thereby save the memory contents. This is particularly valuable for surface operations when significant data is stored in the 95 Mbyte data storage area of the 128 Mbyte DRAM memory.

Unpredictable risk is handled by establishing and managing programmatic and technical reserves (e.g., 1?1{1S'S, power memory). The initial budget reserve was >40% ($42M against a $ 100M scope for the spacecraft system, against which all the reserve was planned) and initial schedule reserve in ATLO was >20 weeks. At this time we are down to our last $300K and 3 days of schedule reserve, which should prove adequate. Figure 5 shows our obligation plans for each fiscal year as a function of consecutive plans. Starting with our first plan in July '93 you can see [bat it wasn't until the start of FY '95 (Oct. '94, CDR was in Sept. '94), that we had a decent estimate of what was ahead anti then we still missed it by about 1096. The cost performance of the various subsystems can be seen in Figure 6. The mechanical and EDL subsystems were the major users of reserves. This was probably the most complex mechanical spacecraft JPL has ever built. The main driver for the. mechanical cost growth was late interface definition driven by evolving 111>1, subsystem designs, particularly the airbags. Science and rover interface changes were. also a driver.

Mass growth has been a constant problem due primarily to the unknowns in the EDL development, particularly the air bags, and their effects on the mechanical integration hardware. Figure 7 shows the mass time history for the entry vehicle.. From our PDR to start of ATLO the mass grew an unbelievable 37 %. From start of ATLO to

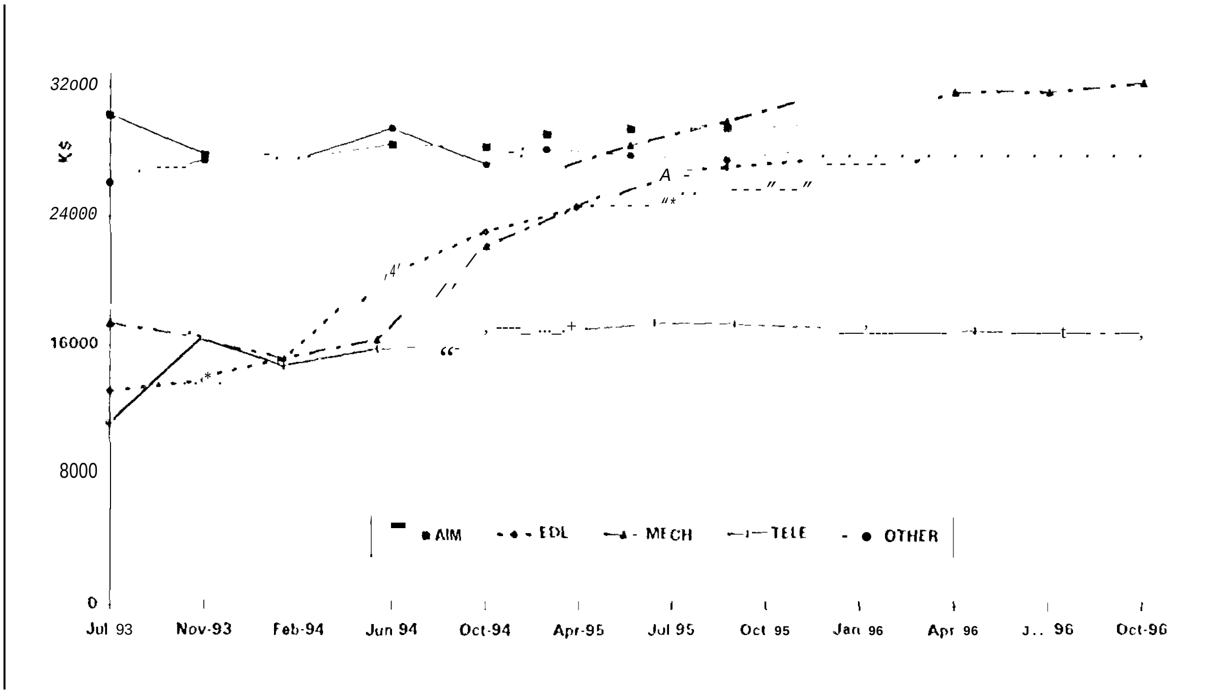

Figure 6. Subsystem Cost History

final spin balance, the mass grew an additional 13%. Much of the mass growth after the start of ATLO came from allocating available reserves to mostly EDL subsystems to increase robustness. The final ballistic coefficient is 63.0 (Viking was 62). In order to maintain control over this critical resource the Flight System Manager personal] y managed the mass list and made all calls on mass increase/ reductions.

Any mission designed to land on the surface of a plaint from spat.c carries with it higher inherent risk than a fly-by or orbiting mission. The risk comes largely from the entry, descent, landing and surface operations phase where the complexities of the required hardware/ software and the uncertainties in the.. environment (e.g. atmospheric density, landing site conditions) make such missions as challenging as they are interesting. The EDL test program was completed in June, 1996 (with the final qualification testing" of the RAD rockets), but this test program evolved and grew significantl y from its start over 3 years ago with scale model airbag testing. The whole EDL test program used full scale and appropriately scaled hardware, testing multiple time.s and involved a wide variety of test conditions. We tied these tests together with a sophisticated set of Monte Carlo analyses. A full up, end-to-end test (i.e., starting, with a high altitude parachute deployment going all the way to landing) was not attempted due to the very high cost and limited value given the problems in testing in the Earth atmosphere and Earth gravity. *The approach of lots of element testing tied together with a Monte Carlo model s eems to be the best possible way to design to a set of conditions which cannot be worst cased. This approach is essential where the designs/models require empirical data and where the design will evolve throughout the test program.*

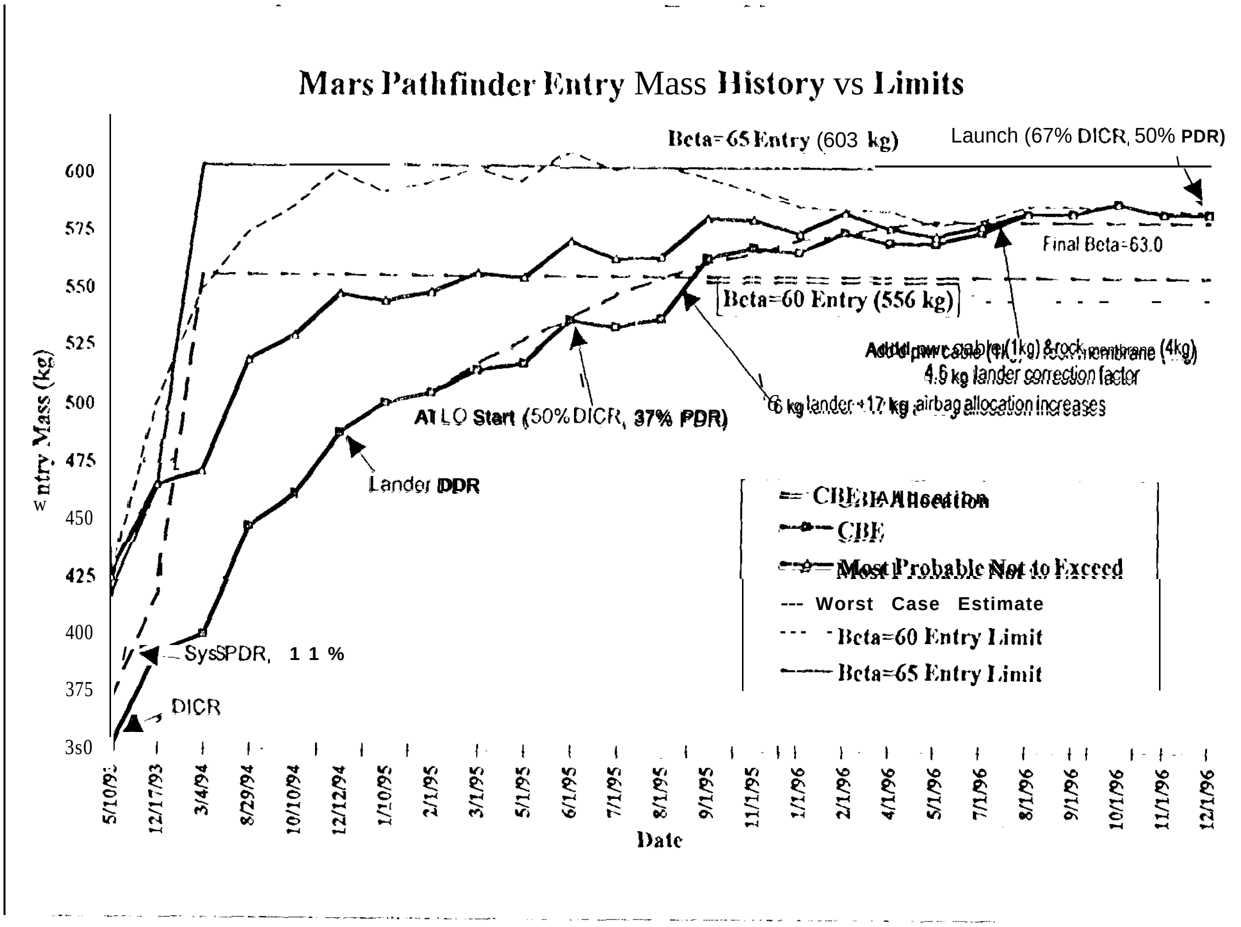

Figure 7, Entry Vehicle Mass Estimate

6. CONCLUSION

The Mars Pathfinder mission is the embodiment of faster (3 years from project start to launch), better (3 spacecraft in one: cruise, entry and lander plus a rover) and cheaper ($171M vs. >$3000M for Viking). In order to be successful within the constraints of this mission, Mars Pathfinder has had to develop and implement a design that inherently takes risk without significantly increasing the likelihood of failure. In order to do this we have had to do many things differently from missions in the recent past. While the design is not fully redundant, the Project has mitigated risk by its robust design, extensive test program (over 2700 hours of system test time) and thorough analysis and simulation activities. While remaining within its budget, the Project has taken no shortcuts or reductions in scope. We have done everything we set out to do and more to assure a successful mission.

The primary key to success has been the exceptional personal commitment of the entire Mars Pathfinder team, including JPL, contractors and other NASA center members, especially the lead engineers and technical managers. The hours are long and the pressure is high but there are great personal rewards in doing this type of challenging mission. The key is the quality and quantity of talented, energetic and motivated people.. At the time of the final edit of this paper, the Mars Pathfinder spacecraft has been successfully launched by its McDonnell Douglas Delta II rocket. Lift-off was 1:58am, Dec. 4, 1996; the injection to Mars was near perfect and all subsystems are operating normally and within expected ranges. Landing on Mars will be July 4, 1997 and we have stayed within the cost cap of $171 M.

ACKNOWLEDGMENTS

The work presented in this paper has been carried out by members of the Mars Pathfinder team at the Jet Propulsion Laboratory, contractor sites all over the United States and at NASA's Ames, Lewis and Langley Research Centers. The author wishes to thank and recognize the entire Mars Pathfinder Team for their outstanding skill and commitment which has enabled such an exciting mission to be accomplished (so far).

REFERENCES

[1] Brian K. Muirhead, "Mars Pathfinder Flight System Design And Implementation, 1995 IEEE Aerospace Applications Conference Proceedings, Feb. 1995.

Brian Muirhead has worked on various spacecraft, science instrument and technology projects at JPL, including Galileo, CRAF/Cassini, Mars Rover Sample Return. He managed the Advanced Spacecraft Development Group and the Mechanical Systems Integration Section. He has led two FBC developments at JPL: the SIR-C Antenna Mechanical System (which flew on STS 59 and 68) and the MSTI 1 Mechanical Subsystems, launched in 1992. He is currently the Flight System Manager for Mars Pathfinder with the responsibility for the design, development, test and launch of the Pathfinder spacecraft. In his "copious" spare time he manages the Champollion Project designing a mission to land on, analyze in situ and return to Earth a sample from a comet. He has a BSME from the University of New Mexico and an MSAE from Caltech.